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SURVEY AND ANALYSIS OF MARINE GAS TURBINE CONTROL AFTER 1975

by

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Marine gas turbine control methods which are presently utilized are adequate for their purpose but do not optimize performance, economy, or maintainability of the shipboard engineering plant. This paper reviews the developments in marine gas turbine propulsion analysis and control since 1975. The review shows that technological advances now present the opportunity to improve present control systems, translating to maneuverability and performance improvements as well as operating cost reduction.

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INTRODUCTION: This paper is a review of published literature on marine gas turbine analysis and control only. Proprietary analyses unquestionably exist, but were not sought out for the purposes of the present review.

Modern marine gas turbine propulsion plants are combined with controllable reversible pitch propellers. This presents the problem of matching the engine RPM to the most efficient pitch, and is accomplished through the use of an integrated throttle control (ITC). Figure 1 shows a block diagram of a typical control scheme.

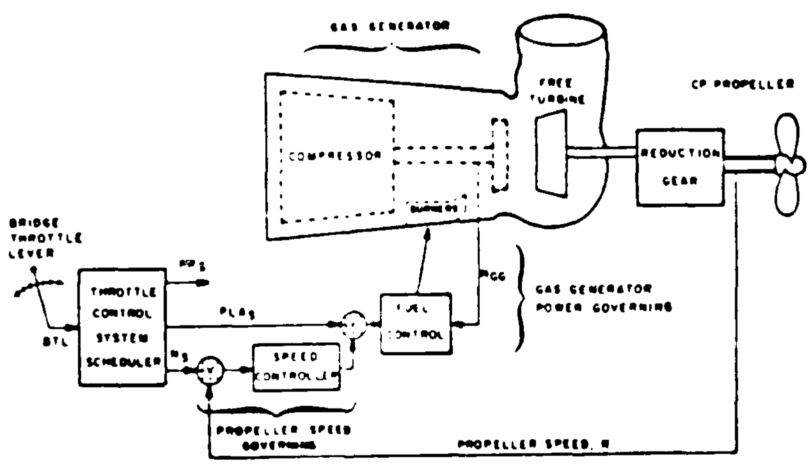

Fig. 1 Typical Marine Gas Turbine Control Scheme

The technology shown in Figure 1 is well over twenty years old and its limitations are now well defined. Today, technology exists that will allow the antiquated analog mechanisms and current computerized systems to be replaced by smaller more reliable digital controls and hardware. The authors suggest that the following could be realized:

1) Reduction of maintenance "nightmares" that develop due to the intricacy and number of small parts in components such as mechanical fuel governors;

2) More reliable and compact circuitry would modify present hardware such as the Free Standing Electronic Enclosure, propulsion and electrical control consoles, and current engine health monitoring equipment;

3) Advances in the ability to model and simulate gas turbine performance would allow plant performance to be significantly improved, thereby increasing plant efficiency and translating to lower operating costs;

4) New techniques in engine health monitoring and analysis provide essential real time data on plant performance to the operators, allowing better and more rapid evaluation and response to a potential or actual engineering casualty;

5) More compatibility between control systems could be achieved, thereby reducing the number of different repair parts that must be stocked in the naval supply system. More commonality would also streamline the training process of personnel responsible for maintaining and operating the systems;

6) Inherent flexibility through reprogramming of computer based controls paves the way for future developments.

CONTROLLER BACKGROUND: During the late seventies and early eighties the marine gas turbine industry hotly debated the pros and cons of analog vs. digital control to implement integrated throttle control (1). The advocates of analog control were of the opinion that this technology was reliable and could perform all necessary calculations required for effective plant control. It was felt that little would be gained in the way of reduction of component count or system reliability through digital systems. This thought process led Rolls Royce to choose analog systems for warship controls, and led General Electric to a similar conclusion for the main fuel control on the LM-2500.

The digital advocates on the other hand, had the foresight to realize that advances in technology would be more easily implemented in a digital base, and that reliability would indeed be as good, if not better than, analog systems. With the advent of the microprocessor, the component count can indeed be reduced with a carefully executed design process. This was demonstrated by the aviation community first on the F-100 engine (10). A natural progression would be for the marine gas turbine community to follow suit. It must be realized that some analog fuel system control components will probably always be required, particularly in the sensing and actuation areas.

Perhaps the most compelling reason today to convert to digital control is the advent of intelligent control. In this approach, a limited amount of operator intervention makes it possible to control a large quantity of measured and unmeasured states to meet the dynamic needs of the plant.

Typically, a good control design approach consists of eleven steps. These steps contain three "feedback loops" which provide the means for modification or improvement should the designer desire. This control design approach is as follows:

1) Specifications for control design;
2) Evaluation of plant function;
3) Plant mathematical modeling;
4) Plant model validation - open loop simulation;
5) Selection of control strategy;
6) Selection of actuators, sensors;
7) Dynamic modeling of actuators, sensors;
8) Selection of controller action;
9) Theoretical controller design;
10) Controller validation - closed loop simulation;
11) Prototype.

The design feedback loops exist between steps 4 and 3, between steps 10 and 8, and between steps 10 and 5. Inherent in this approach is the need for evaluation and modelling of gas turbine performance (step 3). Consequently, while this paper is dealing with marine gas turbines, much early work was done in the area of aviation gas turbine modeling and control. It is only appropriate that we begin with a review of these efforts.

EARLY COMPUTER MODELS: Gas turbines in use today for marine propulsion are for the most part derivatives of aviation gas turbine engines that have been "marinized" for use at sea. As one would expect, several computer simulations were developed to evaluate and predict system performance. The early simulations were developed by the aviation industry and provided a substantial data base for development of more advanced computer models. A short summary of some of the major early aircraft simulations is given below (2):

SMOTE: Developed in 1967 by the Turbine Engine Division of the U.S. Air Force Propulsion Laboratory (AFAPL), Wright-Patterson AFB, Ohio. It us capable of calculating steady-state design and off design performance of a two-spool turbofan engine.

GENENG: Developed in 1972 by NASA's Lewis Research Center (LeRC), Cleveland, Ohio. Its purpose is to improve the versatility of SMOTE. Steady-state design and off design performance of one- and two-spool turbojets can be calculated as well as the two-spool turbofan.

GENENG II: Derivative of GENENG, it calculates steady-state performance of two- or three-spool turbofan engines with as many as three nozzles.

NEPCOMP: Developed in 1974 by the Naval Air Development Center (NADC), Warminister, Pennsylvania. The flexibility inherent to NEPCOMP allows for calculation of steady-state performance of gas-turbine engines with multispools, including turbojets, turbofans, turboshafts, and ramjets.

DYNGEN: Developed in 1975 by LeRC, it combined the capabilities of GENENG and GENENG II for calculating steady-state performance of gas turbine engines with multispools. The additional capability of calculating transient performance was also added.

NNEP: Jointly developed in 1975 by NASA, LeRC, and NADC. This computer code is able to simulate steady-state design and off design performance of almost any conceivable gas turbine engine simulation.

As can be seen above, the majority of the early work was devoted to steady-state simulations. A major shortfall, however, was a lack of dynamic simulation capability. At this point it is prudent to shift the emphasis from the work performed by the aviation industry and concentrate on the contributions made in the marine gas turbine industry in the area of dynamic simulation. Enter David W. Taylor Research and Development Center, Propulsion Dynamics Inc., and the U.S. Naval Postgraduate School.

DYNAMIC COMPUTER MODELS FOR MARINE ENGINE SIMULATION: Engineers at David W. Taylor developed equations to mathematically model various engine manufacturer's configurations (2). Once these were established, a system of common component interface locations was defined and the locations were numbered. Equations were then developed for the numbered major gas turbine components, including compressors, burners, turbines, and engine load. Dynamic equations were then developed to describe speed, power balances, mass accumulation, and energy accumulation.[1] An

1 Information used for this portion of the discussion only relates to a simulation of a single spool engine configuration.

iterative approach was then utilized to balance the performance characteristics of the various engine components. A Newton-Raphson technique was used to achieve convergence. The results of the simulations conducted yielded good results between the manufacturer's simulation and the existing experimental data.

Beginning in the early seventies, the U.S. Navy initiated The Gas Turbine Ship Propulsion Control Systems Research and Development Program. The Navy chose Propulsion Dynamics, Incorporated to conduct the program which was designed to develop a machinery dynamics and control system data base. The program involved computer simulations of total propulsion systems, which were validated by shipboard and model testing. The program continued into the eighties and was still generating technical papers as recently as 1986 (3). The program was successful in developing a theoretical design base for gas turbine propulsion systems. Major conclusions were drawn in the following areas (4):

1) Propulsion systems cycling;
2) Propeller speed governing;
3) Gas generator power governing;
4) Combined Power and Speed Governing.

Based on data obtained during the program, a ship propulsion control system was devised for use in computer simulations. The control system was of the classical integral variety, whose gains were fixed via a "cut and try" method. Gains (Kss= integral speed control gain) were obtained for various wave conditions and engine speeds, then tabulated and compared. In a current application this Kss is set via the "sea state adjust" control found on the propulsion control consoles aboard DD-963 class destroyers. Figure 1 shows a block diagram of the ship propulsion control system used. Simulations performed during the program tended to give good results when compared to model and ship generated data (4).

The program generated some interesting observations regarding a gas turbine engineering plant's response to seaway- and maneuver-induced unsteady loading, which are indeed confirmed by the experience of the first author who served as Main Propulsion Assistant aboard a DD-963 class destroyer. In high seas, gas turbine plants experience a good deal of engine/propeller cycling due to constant changes in propeller loading as the ship moves through the water. A ship configured with two propulsion shafts experiences a good deal of propeller load variation during turns, particularly during high speed turns. Naturally these conditions cause numerous changes in engine speed, resulting in engine wear and potential overspeeding of the engine gas generator should the propulsion load be lost for some reason. It should be noted at this point that these two phenomena can be thought of as "disturbances" to the plant.

Returning to general control development, modern control theory provided the next logical step in controller design. In this work, state space techniques applied to gas turbines have yielded positive results. Such state variable methods allow the control system designer to gain an understanding of the inherent input cross-channel coupling dynamic characteristics of the system and to take advantage of coupling which exists between input and output variables.

In the late seventies students and faculty at the Naval Postgraduate school applied state space techniques to a linearized model of an FFG-7 ship propulsion system (5). Dynamic propulsion system equations were developed for the FFG-7 and then linearized, the appropriate matrices developed, and the dynamic simulations conducted. The results demonstrated that the linear model described the system behavior reasonably well.

Another mathematical model was developed at Tsinghua University, Beijing, China in the mid-eighties (6). A three shaft marine gas turbine was modelled and simulated using state space techniques, and two different numerical methods were used to obtain convergence. The convergence methods used were (a) the varying coefficient method and (b) the small deviation method. The difference in methods lies in the fact that only small system perturbations can be considered in the latter, while large perturbations can be considered in the former. In the first method the initial point of linearization lies in the unsteady regime. The real beauty of the varying coefficient method is that transients under large perturbations can be obtained with sufficient accuracy using linearized equations. Results from the two simulation techniques were compared and the varying coefficient method was deemed more accurate.

RECENT CONTROL DESIGN TECHNIQUES: There are numerous methods by which one can design a controller for an automatic system. When a state space approach is taken to design, there are basically two ways to approach the task: 1) The Pole Placement method and 2) The Linear Quadratic Regulator technique (LQR). The Pole Placement method requires that the location of the desired system closed loop poles be known. Since the optimum closed loop poles of a system may not be known during design, the LQR method is often a better choice. The LQR method optimizes the design of the controller, based on the inputs of various matrices and a cost function. The LQR controller often requires an observer to calculate the states, it then calculates the error between actual and desired states and computes the gains such that stability is guaranteed and the integrated error minimized.

Kidd, Munro, and Winterbone examined the potential of a digital control scheme designed using LQR state space techniques (7). The plant model was one of a two-shaft, two-turbine vessel with a combination of a sprint and a cruise turbine on each shaft coupled to a controllable reversible pitch propeller via a reduction gear. The simulations were performed using a FORTRAN IV digital, non-linear, dynamic computer simulation which included steady state data for the non-linear propeller and thrust characteristics. A digital controller was developed using state space techniques, eventually culminating in a gain-scheduled multivariable controller which was constructed from a selection of linear compensator designs. For comparison purposes a conventional control system was designed as a yardstick by which to measure the digital control system. Both controllers were then implemented in the non-linear ship simulation model. The responses of the two controllers were compared for several maneuvers and the multivariable controller demonstrated a much faster speed of response and less overshoot on propeller-shaft torque output. The multivariable controller constrained the propeller well within safe and acceptable operating limits. The improvements in response of the propulsion plant improved the ship speed response which resulted in ship acceleration and stopping time improvements, i.e ship maneuverability improvements.

LQR controllers have also been designed for the F-401 and F-100 aerospace turbofan engines. Figure 2 is a block diagram of the F-100 control model (10). Similar research was done to apply LQR techniques to the design of a power turbine governor for a turboshaft engine driving a helicopter rotor blade (8). In that work, a GE-700 turboshaft engine was modelled using state space methods and was mathematically coupled to a linear lumped capacitance model of an articulated rotor blade. The two were then combined into an overall system matrix and simulated; the results were compared to a conventional governor's performance. The performance was increased in the areas of time response and overshoot in power turbine speed. These results seem to parallel the results obtained by Kidd, Munro, and Winterbone, but for a different application.

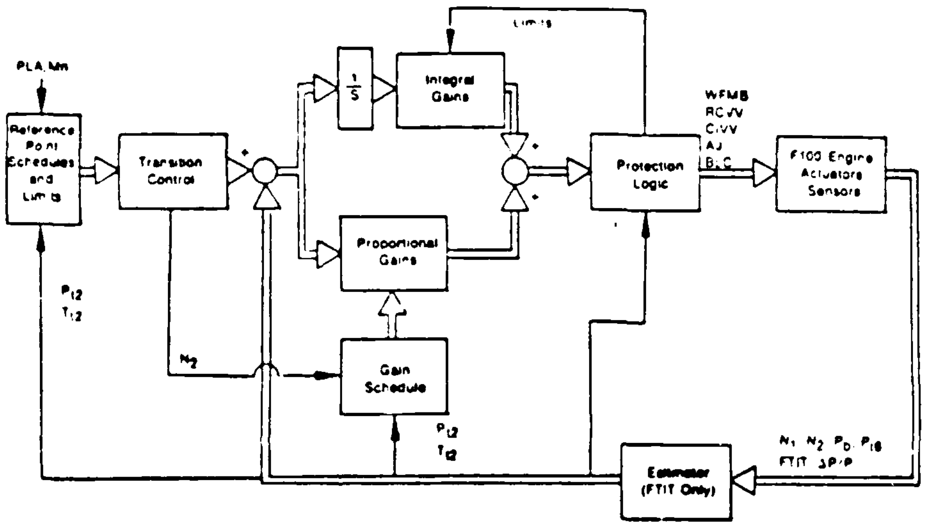

Fig.2 F-100 Control Model

Modelling and simulation work has also been conducted at the Naval Postgraduate School on a Boeing 502-6A engine coupled to a water brake dynamometer that is used to simulate a propulsion load (9). Students and faculty have combined their talents in an ongoing hardware and software implementation process designed to provide a data base for future studies in gas turbine control. Encouraging results have been obtained with the present computer simulation technique, a summary of which are presented in figure 3. The near linearity shown by the experimental data lends great strength to LQR design for marine application.

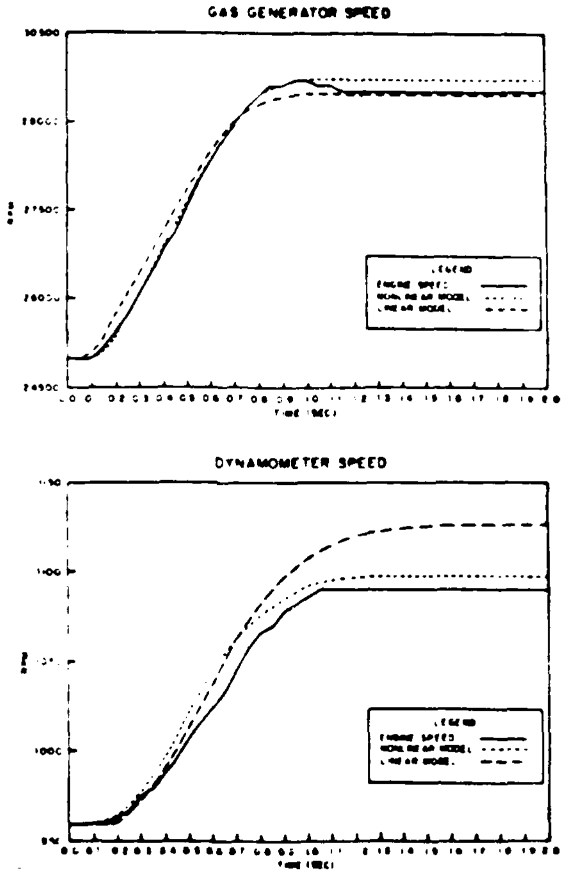

Fig. 3 NPS Boeing 502-6A Computer Simulation Results

FUTURE CONSIDERATIONS: The "Revolution at Sea" concept has forced a departure from the way sea warfare was conducted during World War II and is ushering in technological advances in all phases of naval operations (11). Commensurate with new weapons and tactics will be improvements in hull design, habitability, sensors, and propulsion. Automation will allow modern warships to operate more efficiently and with much smaller crews than World War II ships of similar dimensions. Future ships will be designed with a greater emphasis placed on "ordnance on target", forcing a greater volume of ship space to be used for weapons and their associated systems. Logically, it can be expected that the crews of these ships will be drastically reduced and a large part of the functions performed today by sailors will be automated. This will offer new opportunities in control design and implementation, perhaps including artificial intelligence.

Artificial intelligence may provide a means for decision making where the need for integrated, consistent, rational, real time response exists (12). This concept lends itself well to the propulsion plant environment, particularly during an engineering mechanical casualty (say, due to battle damage or equipment failure).

SUMMARY AND CONCLUSIONS: Existing classical control methods provide a method of controlling gas turbine propulsion plants at an acceptable level. These control schemes have several noteworthy drawbacks, especially the following:

1) Dynamic changes in plant parameters due to changing operating conditions are not totally accounted for;

2) Rate limiting devices associated with classical control

methods may penalize or limit overall plant performance and maneuverability of the ship;

3) Classical control schemes tend to ignore the multivariabe characteristics of a modern propulsion plant, and this may cause inefficient response characteristics to be obtained;

4) Disturbance rejection properties are not as satisfactory or as responsive as a multivariable controller that has been properly designed.

It makes little sense to place a high performance propulsion system on a hull designed for speed and maneuverability (such as today's cruisers, destroyers, and frigates) and then penalize that performance with a less than optimal control system. As the art of war at sea becomes more complex, increased maneuverability and performance may be the keys to a vessel being "in the right place at the right time". Recent advances in multivariable control technology allow the use of much better control schemes to provide ships with the necessary increases in performance.

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